

Energy-saving Resource Allocation by Exploiting the Context Information

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Abstract—Improving energy efficiency of wireless systems by exploiting the context information has received attention recently as the smart phone market keeps expanding. In this paper, we devise energy-saving resource allocation policy for multiple base stations serving non-real-time traffic by exploiting three levels of context information, where the background traffic is assumed to occupy partial resources. Based on the solution from a total energy minimization problem with perfect future information, a context-aware BS sleeping, scheduling and power allocation policy is proposed by estimating the required future information with three levels of context information. Simulation results show that our policy provides significant gains over those without exploiting any context information. Moreover, it is seen that different levels of context information play different roles in saving energy and reducing outage in transmission.

I. INTRODUCTION

Energy efficiency (EE) is one of the major design goal for five-generation (5G) mobile communication systems.

Recently, improving EE by exploiting context information has drawn significant attention as the smart phone popularizes. Context information can be classified into application (e.g., quality of service (QoS)), network (e.g., congestion status), user (e.g., location or mobility pattern), and device levels [1]. The user level context information can be exploited for predicting transmission rate to assist resource allocation in future time. For example, assuming perfect rate prediction, the transmission time or total power was minimized to save power in [2, 3], and a scheduling and antenna closing strategy was proposed to improve EE in [4]. In [2–4], the knowledge of the error-free rate prediction plays important role in power saving, and the base station (BS) is assumed only serving one kind of traffic (e.g., multimedia streaming).

In real-world systems, the predicted channel gains is never error-free. Moreover, a BS may serve multiple classes of traffic, e.g., on demand real-time (RT) traffic such as voice and video that are with high priority, and non-real-time (NRT) traffic such as pre-subscribed file downloading and emails. When there are errors in the predicted future channel gains and only partial resource is available at the BS due to serving other traffic, the predicted transmission rates are inevitably inaccurate, which will lead to the EE reduction.

In this paper, we exploit context information from three levels, application, network and user levels, for energy saving. We design energy-minimizing resource allocation for the user with NRT service when some background traffic such as RT service occupies partial transmission resource. The NRT traffic is often modelled as best effort traffic and is served right after the requests arrive if resource is available. As a result, the spectral efficient or energy efficient optimization for this kind of traffic is usually to maximize the capacity or maximize the EE of the network. Nonetheless, if we know the expected time to accomplish the service either by user subscription or by user behavior prediction, e.g., for a user-subscribed file downloading with a desired deadline, it is possible to further save energy with long term resource allocation by waiting for better channel condition and network status.

To demonstrate how such an application level context information can be exploited to save energy, we artificially model the NRT service as transmitting a given amount of data in a long duration but with a deadline, which can reflect some emerging mobile video traffic based on subscription or popular file prefetching based on user interest prediction. By formulating and solving a total energy minimizing problem with perfect future information, the optimal resource allocation policy is obtained, which provides the intuition on how to exploit context information as well as a performance upper bound. By estimating the required future information with three levels of context information, a BS sleeping, scheduling and power allocation policy is then proposed. Simulation results show that the proposed policy provides substantial gain in saving energy over those not exploiting the context information. Moreover, the context information from the application and users helps save energy and that from network helps reduce outage probability.

II. SYSTEM MODEL

A. Traffic Model and System Model

Consider a downlink multicell system. M BSs each equipped with N_t antennas serve a single antenna user moving across the cells who demands NRT traffic over multiple time slots, where each BS also serves randomly arrived RT traffic requests. To capture the essence of the problem, we only consider the simple scenario of one user with NRT traffic, and leave the issues for multi-user scenario in future work. The

maximal transmit power of each BS is P_{\max} , and the maximal available bandwidth is W_{\max} .

The RT traffic has QoS provision and needs to be served immediately after the requests arrive the BS. To ensure the QoS of the RT traffic, a given portion of the resources need to be reserved for each request [5]. In practice, since the requests arrive randomly, the resource used by these requests is time-varying. The transmit power and bandwidth occupied by the RT traffic of the i th BS in the t th time slot are denoted as $p_{i,\text{RT}}^t$ and $W_{i,\text{RT}}^t$, respectively.

The NRT traffic can be modelled as a problem to convey a given number of bits B within a duration of T time slots, where the duration is much longer than the transmission time (say, on the order of minutes or even hours). If the B bits are not reliably transmitted within the duration, an outage occurs.

Since the NRT traffic is less urgent, the NRT user can use the remaining transmit power and bandwidth of the RT traffic. Suppose that the request of the NRT user arrives at the first time slot. We can select proper time slots with proper transmit power to serve the user in order to save energy. Denote $\mathbf{m}_i = [m_i^1, \dots, m_i^T]^H$ as the indicator of scheduling status for the NRT user by the i th BS, where $m_i^t \in \{0, 1\}$. When $m_i^t = 1$, the user is scheduled in the t th time slot by the i th BS. When $m_i^t = 0$, the user is not scheduled by the i th BS. For simplicity, we assume that the user is only served by the closest BS in each time slot, which allows us exploiting the user level context information as will be clear later.

For the user with NRT traffic, the received signal in the t th time slot can be expressed as

$$y^t = m_i^t \sqrt{\alpha^t} (\mathbf{h}^t)^H \mathbf{w}^t \sqrt{p^t} x^t + n^t, \quad (1)$$

where x^t is the transmit symbol for the user in the t th time slot with $\mathbb{E}\{|x^t|^2\} = 1$ and $\mathbb{E}\{\cdot\}$ represents expectation, p^t is the transmit power, $\mathbf{w}^t \in \mathbb{C}^{N_t \times 1}$ is the beamforming vector, α^t is the large-scale fading gain including path loss and shadowing between the user and the closest BS, $\mathbf{h}^t \in \mathbb{C}^{N_t \times 1}$ is the independent and identically distributed (i.i.d.) small scale Rayleigh fading channel vector, and n^t is the noise with variance σ^2 . Since the NRT user is scheduled only by one BS in each time slot, maximum ratio transmission is optimal, i.e., $\mathbf{w}^t = \mathbf{h}^t / \|\mathbf{h}^t\|$, where $\|\cdot\|$ denotes Euclidean norm.

In the t th time slot, the achievable rate of the user is

$$R^t = m_i^t W_i^t \log_2(1 + g^t p^t), \quad (2)$$

where $W_i^t \triangleq W_{\max} - m_{i,\text{RT}}^t W_{i,\text{RT}}^t$ is the available bandwidth for the NRT user in the t th time slot, $g^t \triangleq \alpha^t \|\mathbf{h}^t\|^2 / (G\sigma^2)$ is the equivalent channel gain, and G is the signal-to-noise ratio (SNR) gap that reflects the gap between the capacity-achieving and practical modulation and coding selection (MCS) transmit policies [6]. The SNR gap depends on the practically-used MCS and the targeted error probability.

B. Power Model

Because we strive to save energy by long term resource allocation for the NRT traffic, the RT service is called background traffic in the rest of the paper.

In the t th time slot, the power consumed by the background traffic of BSs (referred to as *basic power* in the sequel) can be modeled as [7]

$$P_B^t = \sum_{i=1}^M \left(\frac{1}{\xi} p_{i,\text{RT}}^t + \text{Sign}(p_{i,\text{RT}}^t) (P_{\text{act}} - P_{\text{sle}}) + P_{\text{sle}} \right), \quad (3)$$

where ξ is the power amplifier (PA) efficiency, P_{act} and P_{sle} are the circuit power consumption when the BS is in active and sleeping mode, respectively, and $\text{Sign}(x) = \begin{cases} 1, & x > 0 \\ 0, & \text{else} \end{cases}$.

Further considering the power consumed by the NRT traffic, the total power consumption at the BSs in the t th time slot is,

$$P^t = \sum_{i=1}^M \frac{1}{\xi} (p_{i,\text{RT}}^t + m_i^t p^t) + \sum_{i=1}^M (\text{Sign}(p_{i,\text{RT}}^t + m_i^t p^t) (P_{\text{act}} - P_{\text{sle}}) + P_{\text{sle}}). \quad (4)$$

III. RESOURCE ALLOCATION WITH FUTURE INFORMATION

In this section, we optimize scheduling and power allocation for the NRT user to minimize the total energy consumed in the T time slots. To provide a performance upper bound and gain insights on how to design a viable resource allocation, we assume that when optimizing at the t th time slot all the information during T time slots are perfectly known, which include equivalent channel gain g^t of the NRT user, the bandwidth W_i^t and transmit power $p_{i,\text{RT}}^t$ occupied by the background traffic at the i th BS in all time slots, $t = 1, \dots, T$.

For the user with NRT traffic, the requested B bits need to be transmitted before the deadline. The resource allocation problem to minimize the overall energy consumption in T time slots under this constraint can be formulated as follows,

$$\min_{\mathbf{p}, \mathbf{m}} \sum_{t=1}^T P^t \Delta_T \quad (5a)$$

$$\text{s.t.} \quad \sum_{t=1}^T m_i^t W_i^t \log_2(1 + g^t p^t) \Delta_T = B, \quad (5b)$$

$$p^t \geq 0, m_i^t p^t + p_{i,\text{RT}}^t \leq P_{\max}, \quad (5c)$$

$$t = 1, \dots, T, i = 1, \dots, M,$$

where $\mathbf{p} = [p^1, \dots, p^T]^H$ is the power allocation of the user during all T time slots, $\mathbf{m} = [\mathbf{m}_1, \dots, \mathbf{m}_M]$ is the scheduling status matrix of all BSs during all time slots, and Δ_T is the duration of each time slot. (5b) is the transmission constraint of the NRT user, (5c) is the power constraint of the BSs.

Since the NRT user is only accessed by the closest BS in each time slot, we omit subscript i of $m_i^t, p_{i,\text{RT}}^t, W_i^t$ for notation simplicity. Then, $m^t, p_{\text{RT}}^t, W^t$ represent the indicator of whether the NRT user is scheduled by its closest BS, the power allocated to the user, and the available bandwidth of the closest BS in the t th time slot, respectively.

According to whether the closest BS is occupied or free from the background traffic, we divide the T time slots into busy time and idle time. Denote $\mathcal{T}_{\text{oc}} = \{t | p_{\text{RT}}^t > 0\}$ with cardinality T_{oc} as the index set of the busy time slots, and denote $\mathcal{T}_{\text{id}} = \{t | p_{\text{RT}}^t = 0\}$ with cardinality $T_{\text{id}} = T - T_{\text{oc}}$ as the index set of the idle time slots. Then, \mathcal{T}_{id} is the complementary set of \mathcal{T}_{oc} , as illustrated in Fig. 1.

To fully utilize the transmit power and bandwidth at the BS, the user with NRT traffic may be served in both kinds of time slots. Then, from (3) and (4), the overall energy consumption in the T time slots can be rewritten as follows,

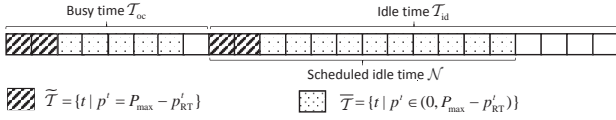


Fig. 1. Illustration of several sets of the time slots. To help understand, we have re-ordered the T time slots, where the equivalent channel gains in idle time slots are in a descending order.

$$\sum_{t=1}^T P^t \Delta T = \underbrace{\sum_{t=1}^T P_B^t \Delta T}_{\text{Basic Power}} + \underbrace{\sum_{t=1}^T \frac{1}{\xi} m^t p^t \Delta T}_{\text{Transmit Power}} + \underbrace{\sum_{t \in \mathcal{T}_{id}} m^t (P_{act} - P_{sle}) \Delta T}_{\text{Circuit Power}},$$

which includes the basic power consumed for background traffic, transmit power for NRT traffic, and extra circuit power for the NRT traffic in idle time slots. Since the basic power is not affected by the resource allocation for the NRT traffic, minimizing the overall energy consumption is equivalent to minimizing the sum of the second and third terms.

Denote $\mathcal{N} = \{t | m^t = 1, t \in \mathcal{T}_{id}\}$ as the index set of scheduled idle time slots for the NRT user. Then, $N \triangleq \sum_{t \in \mathcal{T}_{id}} m^t$ is the number of the scheduled idle time slots. During the non-scheduled idle time slots, the transmit power allocated to the NRT user is zero, i.e., $p^t = 0, m^t = 0, t \in \mathcal{T}_{id} - \mathcal{N}$, and the BS is turned into sleeping mode. Consequently, problem (5) can be equivalently transformed into the following problem

$$\min_{p, N} \sum_{t \in \mathcal{T}_{oc} \cup \mathcal{N}} \frac{1}{\xi} p^t \Delta T + N(P_{act} - P_{sle}) \Delta T \quad (6a)$$

$$s.t. \sum_{t \in \mathcal{T}_{oc} \cup \mathcal{N}} W^t \log_2(1 + g^t p^t) \Delta T = B, \quad (6b)$$

$$p^t \geq 0, p^t + p_{RT}^t \leq P_{max}, t \in \mathcal{T}_{oc} \cup \mathcal{N}, \mathcal{N} \subseteq \mathcal{T}_{id}. \quad (6c)$$

After $p^t, t = 1, \dots, T$ and N are found, the solution of m^t can be obtained as will be stated later.

To solve problem (6), we first optimize p^t with given N and then exhaustively search the optimal value of N from T_{id} to 1 that minimizes the total energy consumption.

When N is given, the transmit power can be obtained from the following standard power allocation problem

$$\min_p \sum_{t \in \mathcal{T}_{oc} \cup \mathcal{N}} \frac{1}{\xi} p^t, \quad (7)$$

$s.t. \text{ (6b), (6c).}$

whose optimal solution can be found by water-filling, i.e.,

$$p^t = \left(\xi \nu W^t \log_2 e - \frac{1}{g^t} \right)_0^{P_{max} - p_{RT}^t}, t \in \mathcal{T}_{oc} \cup \mathcal{N}, \quad (8)$$

where $(\cdot)_0^{P_{max} - p_{RT}^t}$ represents $0 \leq p^t \leq P_{max} - p_{RT}^t$, and ν is Lagrange multiplier.

Denote $\tilde{\mathcal{T}} = \{t | p^t = P_{max} - p_{RT}^t\}$ as the index set of the time slots when the NRT user is served with all remaining transmit power $P_{max} - p_{RT}^t$, and $\bar{\mathcal{T}} = \{t | p^t \in (0, P_{max} - p_{RT}^t)\}$ as the index set of the time slots when $p^t < P_{max} - p_{RT}^t$. Then, the Lagrange multiplier can be expressed as follows,

$$\nu = \frac{2}{\xi \prod_{t \in \tilde{\mathcal{T}}} (W^t g^t) \sum_{t \in \bar{\mathcal{T}}} W^t \Delta T} \ln 2. \quad (9)$$

With (8), (6a) becomes a function of N . Then, the optimal number of the scheduled idle time slots can be found from $N^* = \arg \min_N \sum_{t \in \mathcal{T}_{oc} \cup \mathcal{N}} \frac{1}{\xi} p^t \Delta T + N(P_{act} - P_{sle}) \Delta T$ by exhaustive searching. With N^* , the optimal power allocation during all the T time slots can be obtained as

$$p^{t*} = \begin{cases} \left(\xi \nu^* W^t \log_2 e - \frac{1}{g^t} \right)_0^{P_{max} - p_{RT}^t}, & t \in \mathcal{T}_{oc} \cup \mathcal{N}^* \\ 0, & t \in \mathcal{T}_{id} - \mathcal{N}^* \end{cases} \quad (10)$$

where ν^* is the Lagrange multiplier of problem (7) for N^* , and \mathcal{N}^* is index set of the scheduled N^* idle time slots.

From the water-filling structure of power allocation in (10), we can see that \mathcal{N}^* is the N^* idle time slots with highest equivalent channel gains. Consequently, \mathcal{N}^* can be obtained as $\{t | g^t \geq g_{th}^*, t \in \mathcal{T}_{id}\}$, where the equivalent channel gains of N^* idle time slots exceed the threshold g_{th}^* .

Then, the optimal power allocation to the NRT user can be accomplished with the following *PC-Algorithm*.

- When the BS is in busy time, the allocated power is $p^{t*} = \left(\xi \nu^* W^t \log_2 e - \frac{1}{g^t} \right)_0^{P_{max} - p_{RT}^t}$.
- When the BS is in idle time (i.e., $p_{RT}^t = 0$, hence, $W^t = W_{max}$), if the channel condition is good enough such that $g^t \geq g_{th}^*$, the allocated power is $p^{t*} = \left(\xi \nu^* W_{max} \log_2 e - \frac{1}{g^t} \right)_0^{P_{max}}$. Otherwise, no power is allocated.

With p^{t*} , the optimal scheduling indicator for the NRT user can be obtained as $m^{t*} = \text{Sign}(p^{t*}), t = 1, \dots, T$. When $p^{t*} = 0, t \in \mathcal{T}_{id} - \mathcal{N}^*$, the BS turns into sleeping mode.

Remark 1: The power allocated in the t th time slot depends on the information in this time slot including the equivalent channel gain g^t , available bandwidth W^t and transmit power p_{RT}^t , as well as the information in other time slots implicitly included in the Lagrange multiplier ν^* and threshold g_{th}^* . It is noteworthy that the power allocation among the T time slots shares the same Lagrange multiplier ν^* and threshold g_{th}^* .

IV. RESOURCE ALLOCATION WITH CONTEXT INFORMATION

PC-Algorithm provided in last section is only viable if the information during the T time slots can be estimated. In practice, however, when optimizing the resource allocation for the NRT users in the t th time slot, only current information g^t, W^t and p_{RT}^t are known. The future information after t th time slot is hard to predict accurately, especially the small scale fading gains and excess resources available for the NRT traffic at each BS. Fortunately, only the Lagrange multiplier ν^* and threshold g_{th}^* depend on the information from future time slots. Inspired by this observation, in the sequel we estimate these two parameters with the help of context information.

A. Estimation of Lagrange Multiplier ν^*

Recall that ν^* is the optimal Lagrange multiplier obtained from problem (7) with given N^* . From the procedure of finding the optimal resource allocation with future information, we know that to estimate ν^* we need to estimate N^* and \mathcal{T}_{oc} , as well as the values of g^t, W^t and p_{RT}^t during T time slots.

We exploit the network and user level context information to help estimate these values and finally estimate ν^* .

Busy time \mathcal{T}_{oc} (or equivalently its complementary set \mathcal{T}_{id}) reflects the resource utilization status, which can be estimated from *network level context information*, i.e., the average number of busy time slots \hat{T}_{oc} from the statistics of traffic load in the past in real-world systems. With the estimated value \hat{T}_{oc} , we can estimate the busy time slots set $\hat{\mathcal{T}}_{oc}$ by randomly choosing \hat{T}_{oc} elements from $\{1, \dots, T\}$. Because $\hat{\mathcal{T}}_{oc}$ is used for estimating ν^* rather than truly applied for allocating resource, such a random guess causes little performance loss as will be shown in simulations later. Then, the estimated index set of idle time slots $\hat{\mathcal{T}}_{id}$ is the complementary set of $\hat{\mathcal{T}}_{oc}$ with cardinality $\hat{T}_{id} = T - \hat{T}_{oc}$.

Equivalent channel gain g^t includes both large and small channel fading gains, which can be estimated from *user level context information*, i.e., the predicted trajectory of a mobile NRT user in a given period and the corresponding average speed. Since the smart phones popularize and the human behavior becomes predictable, it is possible to estimate the trajectory in a given period, which can be divided into different parts according to the average speeds, say when a user takes different kinds of transportation. Then, the large scale fading gains can be obtained from the long term location prediction [8]. Based on the *user level context information*, the user locations can be roughly predicted, and finally the large scale fading gains of the user during the T time slots can be estimated as $\hat{\alpha}^1, \dots, \hat{\alpha}^T$. Considering that $\mathbb{E}\{\|\mathbf{h}^t\|^2\} = N_t$, the equivalent channel gains can be estimated as $\hat{g}^t, t = 1, \dots, T$, where $\hat{g}^t = N_t \hat{\alpha}^t / (G\sigma^2)$.

Bandwidth $W_{\max} - W^t$ and transmit power p_{RT}^t are the resources occupied by RT traffic during busy time slots, which are hard to predict due to the randomness of the arrived request. To ensure the B bits of the NRT traffic being able to be conveyed within T time slots, we simply assume the worst case where no bandwidth and power are left for the NRT traffic when a BS is busy with RT traffic based on the estimated busy time set $\hat{\mathcal{T}}_{oc}$ from *network level context information*.

The variable N^* is the optimal number of the scheduled idle time slots. Using the context information to problem (6), N^* can be estimated from the following problem

$$\min_{\hat{\mathbf{p}}, \hat{\mathcal{N}}} \sum_{t \in \hat{\mathcal{N}}} \frac{1}{\xi} \hat{p}^t \Delta_T + \hat{N} (P_{act} - P_{sle}) \Delta_T \quad (11a)$$

$$s.t. \sum_{t \in \hat{\mathcal{N}}} W_{\max} \log_2(1 + \hat{g}^t \hat{p}^t) \Delta_T = B, \quad (11b)$$

$$\hat{p}^t \geq 0, p^t \leq P_{\max}, t \in \hat{\mathcal{N}} \subseteq \hat{\mathcal{T}}_{id} \quad (11c)$$

where \hat{p}^t is obtained to help estimate N^* , and $\hat{\mathcal{N}}$ is the index set of scheduled idle time slots, which is a subset of the estimated idle time slot set $\hat{\mathcal{T}}_{id}$.

The solution of problem (11) can be found by using the similar way as solving problem (6). The optimal number of scheduled idle time slots can be estimated as \hat{N}^* , and finally the estimated Lagrange multiplier $\hat{\nu}^*$ can be obtained with \hat{N}^* .

B. Estimation of Threshold \hat{g}_{th}^*

Recall that \hat{g}_{th}^* is used to select N^* idle time slots from the set \mathcal{T}_{id} with highest equivalent channel gains. Since \hat{N}^* and

$\hat{\mathcal{T}}_{id}$ are inevitably with estimation errors, intuitively setting the threshold according to the estimated values of \hat{g}^t and N^* may lead to insufficient number of scheduled idle time slots, which results in outage in the transmission. In order to control the outage probability, we find a conservative threshold. To this end, we ensure the probability that at least \hat{N}^* idle time slots will be scheduled is close to one, i.e.,

$$\Pr(n \geq \hat{N}^*, t \in \hat{\mathcal{T}}_{id}) = 1 - \epsilon, \quad (12)$$

where ϵ is a small value to control the outage probability.

With the help of network and user level context information, we obtain a closed form expression of the probability in the following proposition, where the accuracy of the approximation will be evaluated later via simulations.

Proposition 1: When T and \hat{T}_{id} are large, the probability that at least \hat{N}^* idle time slots are scheduled can be approximated as follows,

$$\Pr(n \geq \hat{N}^*, t \in \hat{\mathcal{T}}_{id}) \approx \sum_{n=\lceil \hat{N}^* T / \hat{T}_{id} \rceil}^T \binom{T}{n} (q)^n (1-q)^{T-n} \quad (13)$$

where $\lceil \cdot \rceil$ is the ceiling function,

$$q = \frac{1}{T} \sum_{t=1}^T \sum_{i=0}^{N_t-1} \frac{1}{i!} \left(\frac{G\sigma^2}{\hat{\alpha}^t} \hat{g}_{th} \right)^i e^{-\frac{G\sigma^2}{\hat{\alpha}^t} \hat{g}_{th}}, \quad (14)$$

and \hat{g}_{th} is the estimated threshold.

Proof: See Appendix A. ■

Since a higher threshold means that less idle time slots will be scheduled, the probability $\Pr(n \geq \hat{N}^*, t \in \hat{\mathcal{T}}_{id})$ is a decreasing function of the threshold \hat{g}_{th} . Then, by substituting (13) into (12), q can be found numerically by bisection searching. Further using (14), the estimated threshold \hat{g}_{th}^* satisfying (12) can be finally obtained by bisection searching.

Remark 2: The proposed BS sleeping, scheduling and power allocation policy is implemented as follows. When the request of the NRT user arrives at the 1st time slot, we can estimate the two parameters ν^* and \hat{g}_{th}^* with available context information using the method proposed in this section. Then, when we design the resource allocation in the t th time slot, by using the values of \hat{g}^t , W^t and p_{RT}^t that are available in current time instant, *PC-algorithm* can be applied to obtain p^{t*} , and the scheduling can be obtained as $m^{t*} = \text{Sign}(p^{t*})$. When $p^{t*} = 0$, $t \in \mathcal{T}_{id} - \mathcal{N}$, the BS goes to sleeping mode.

V. SIMULATION

In this section, we evaluate the proposed context-aware resource allocation by simulations.

The simulation setups are shown in Fig. 2. To reflect the resource utilization of busy BSs, the requests of background traffic is modeled as Poisson process with average rate λ_1 and λ_2 for the 1st and 2nd BSs, and the service time of each request follows exponential distribution with mean $V = 2$ time slots [5]. Each request with background traffic is assumed to occupy the same transmit power of 8 W and bandwidth of 2 MHz. Then, a BS can serve at most $N_C = 5$ requests of background traffic in one time slot, and the newly arrived request will not be admitted if the BS has been fully occupied. Based on this request model of the background traffic, the average number of idle time slots for the i th BS during T time slots can be obtained as $\hat{T}_{id} = \sum_{i=1}^2 \Pr_{id}(i) T_i$,

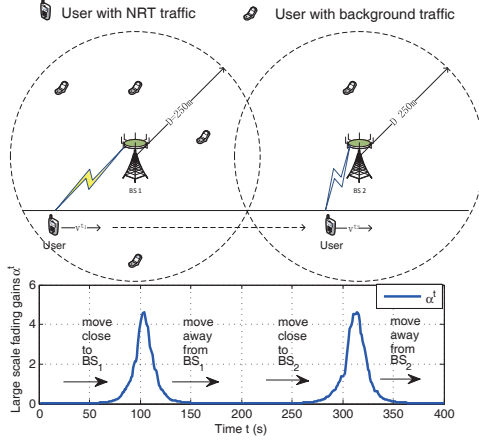


Fig. 2. Two macro cells with radius $D = 250$ m, $N_t = 4$, the two BSs alternatively serve a mobile user with NRT traffic in T time slots each with interval of $\Delta_T = 1$ s when there are random arrival background requests. The maximal transmit power and bandwidth of each BS are $P_{\max} = 40$ W and $W_{\max} = 10$ MHz. The path loss model is $15.3 + 37.6 \log_{10}(d)$, where d is the distance between the BS and user in meter [9]. The cell-edge SNR is set as 5 dB, which is the SNR received at the distance D when a BS transmits with P_{\max} , reflecting both noise and intercell interference. The small scale channel is subject to Rayleigh block fading. The circuit power consumption parameters are $P_{\text{act}} = 233.2$ W, $P_{\text{sle}} = 150$ W, and $\xi = 21.3\%$ [7].

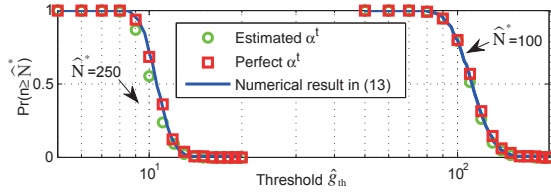


Fig. 3. The accuracy of the approximation of $\Pr(n \geq \hat{N}^*, t \in \hat{T}_{\text{id}})$ when α^t is perfectly known and is estimated with errors, $T = 1000$, $\hat{T}_{\text{id}} = 500$.

where $\Pr_{\text{id}}(i) = 1 / (\sum_{n=0}^{N_c} (\lambda_i V)^n / n!)$ obtained in [10] is the probability that the i th BS is idle, and T_i is the duration when NRT user is in the i th cell. When $\lambda_i = 0.2$, the probability is 0.67, i.e., 67% time slots are idle.

The user with NRT traffic moves across the two macro cells along a line with speed v^t uniformly distributed in $(0, 5)$ m/s, i.e., during the t th time slot, the user is in constant speed v^t and in each time slot, the speed is different. Therefore, the average speed during T time slots is 2.5 m/s from which we can roughly estimate the large scale fading gains. $B = 5$ GBits of data need to be conveyed within the T time slots. Shannon Capacity is considered in (2), i.e., $G = 0$ dB. The results are obtained from 100 Monte Carlo trails.

We first validate the approximation in Proposition 1. From the simulated probability $\Pr(n \geq \hat{N}^*, t \in \hat{T}_{\text{id}})$ with given \hat{N}^* and \hat{T}_{id} as well as the numerical results in Fig. 3, we can see that the approximation is accurate.

To show the impact of different context information on saving energy, the following approaches are simulated. With all approaches, the BS will turns into sleep mode when there is no any traffic to serve.

- 1) *SE-maximizing without context information* (Legend “SE-No context”): Without considering context infor-

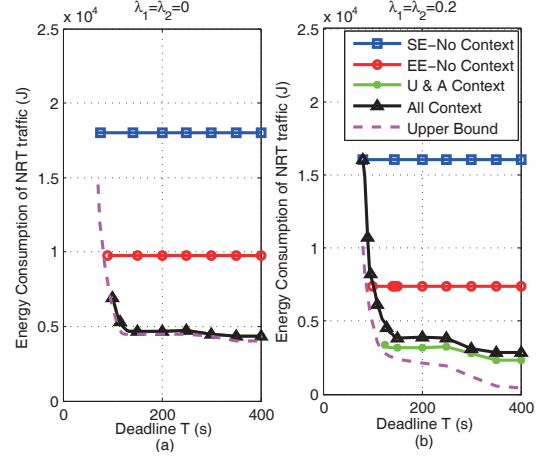


Fig. 4. Energy consumption of NRT traffic versus deadline T .

mation, the BS serves the NRT traffic as best effort service that maximizes the capacity in each time slot, i.e., $p^t = P_{\max} - p_{\text{RT}}^t$.

- 2) *EE-maximizing without context information* (Legend “EE-No Context”): The BS maximizes the ratio of the instantaneous rate transmitted and the power consumed in each time slot.
- 3) *Resource allocation with user and application level context information* (Legend “U&A Context ”): The BS estimates the Lagrange multiplier and threshold without considering the context information from network, i.e., without the worst case assumption.
- 4) *Resource allocation with network, user and application level context information* (Legend “All Context ”): This is the proposed context-aware resource allocation.
- 5) *Resource allocation with all future information* (Legend “Upper Bound”): This is the optimal solution in section III with perfect future information, which provides the performance upper bound.

Since context information is exploited to save energy for the NRT traffic, we only show the results for this kind of traffic, which is the total energy consumption minus the basic energy consumption, $\sum_{t=1}^T (P^t - P_B^t) \Delta_T$.

In Fig. 4, we show the impact of the deadline of NRT traffic on energy saving, where only the results without outage are presented. We can see that with the increase of deadline T , the SE- and EE-maximizing approaches consume more energy than the proposed context-aware resource allocation due to not considering the application level context information. Moreover, the energy consumption of the proposed method decreases as the deadline increases. When BSs are without background traffic (i.e., in Fig. 4(a)), the proposed method almost performs the same as the upper bound, which implies that the rough knowledge of user level context information is good enough to estimate the two parameters, ν^* and g_{th}^* . When the BSs are with background traffic (i.e., in Fig. 4(b)), there is a gap between “All Context” and “Upper Bound”, which comes from the worst case assumption on the network

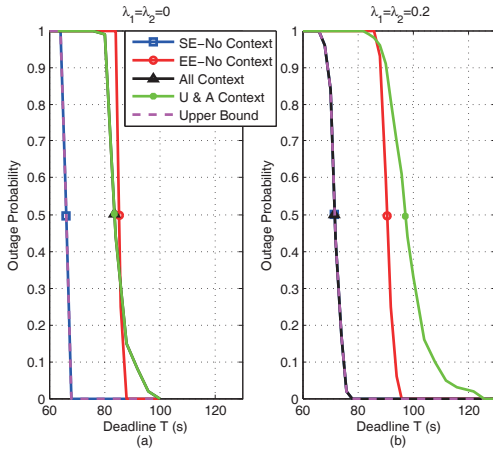


Fig. 5. Outage probability versus deadline T .

level context information when we estimate parameter $\hat{\nu}^*$. Comparing Fig. 4(a) with Fig. 4(b), we see that the energy consumption is lower when the background traffic exists and T is large, because there are more chances to transmit in the busy time slots, which reduces the circuit energy consumption for the NRT traffic. “All Context” consumes a little more energy than “U&A Context”. This is because the transmission is more conservative when considering the network level context information, in order to ensure lower outage probability.

In Fig. 5, we show the outage probability corresponding to Fig. 4. When there is no background traffic, the context-aware resource allocation yields similar outage probability to the EE-maximizing method without context information. When there exists background traffic as in Fig. 5(b), the context information from network helps reduce the outage probability. Note that in Fig. 4(b) the performance exploiting and not exploiting the context information from network are close. This indicates that the context information from the application and users helps save the energy and that from the network helps reduce the outage probability.

VI. CONCLUSION

In this paper, we proposed a context-aware resource allocation policy for the non-real-time traffic when the BS is occupied by background traffic. The application, user and network levels context information were exploited to save energy. Simulation results showed that the application and user levels context information can help save energy, and the network level context information can help reduce the outage probability in transmission.

APPENDIX A PROOF OF PROPOSITION 1

Because \hat{T}_{id} is estimated as a random guess from $\mathcal{T} \triangleq \{1, \dots, T\}$, \hat{T}_{id} can be viewed as \hat{T}_{id} samples from the statistical population \mathcal{T} . Consequently, the probability to select N^* samples from \hat{T}_{id} is equal to the probability to select $\lceil N^*T/\hat{T}_{id} \rceil$ samples from \mathcal{T} when T and \hat{T}_{id} approach infinity. Therefore, when T and \hat{T}_{id} are large, we have

$$\Pr(n \geq \hat{N}^*, t \in \hat{T}_{id}) \approx \Pr(n \geq \lceil \frac{\hat{N}^*T}{\hat{T}_{id}} \rceil, t \in \mathcal{T}). \quad (15)$$

Without loss of generality, the values of equivalent large scale fading gains and their estimates $\alpha^t, \hat{\alpha}^t, t \in \mathcal{T}$ are within a range of $[\alpha_{\min}, \alpha_{\max}]$. We divided the range into J intervals as $\delta_1, \dots, \delta_J$, where $\delta_j = [\alpha_{\min} + (j-1)\delta, \alpha_{\min} + j\delta]$, and $\delta = (\alpha_{\max} - \alpha_{\min})/J$. The number of $\hat{\alpha}^t, t \in \mathcal{T}$ located in the interval δ_j is denoted as x_j .

Construct a sequence of i.i.d variables $\beta^t, t \in \mathcal{T}$, whose probability mass function is $\Pr(\beta^t = \hat{\alpha}^i) = \frac{1}{T}, i \in \mathcal{T}$. Then, the probability that β^t is located in the interval δ_j is $\Pr(\beta^t \in \delta_j) = x_j/T$. When $T \rightarrow \infty$, based on Borel’s law of large numbers, the average number of $\beta^t, t \in \mathcal{T}$ located in the interval δ_j is $\mathbb{E}\{x_j\} = \lim_{T \rightarrow \infty} x_j = \Pr(\beta^t \in \delta_j)T = x_j$. Therefore, we can use $\beta^t, t \in \mathcal{T}$ to approximate $\hat{\alpha}^t, t \in \mathcal{T}$. Further considering that $\|\mathbf{h}^t\|^2, t \in \mathcal{T}$ are i.i.d., the probability to select $\lceil \frac{\hat{N}^*T}{\hat{T}_{id}} \rceil$ equivalent channel gains from $g^t = \alpha^t \|\mathbf{h}^t\|^2 / (G\sigma^2), t \in \mathcal{T}$ can be approximated as the probability to select same number of values from $\beta^t \|\mathbf{h}^t\|^2 / (G\sigma^2), t \in \mathcal{T}$, i.e.,

$\Pr(n \geq \lceil \frac{\hat{N}^*T}{\hat{T}_{id}} \rceil, t \in \mathcal{T}) \approx \sum_{n=\lceil \hat{N}^*T/\hat{T}_{id} \rceil}^T \binom{T}{n} (q)^n (1-q)^{T-n}$, where q is the probability that $\beta^t \|\mathbf{h}^t\|^2 / (G\sigma^2)$ exceeds the threshold \hat{g}_{th} . Then, together with (15), we have (13).

Because $\|\mathbf{h}^t\|^2$ follows Gamma distribution $\mathbb{G}(N_t, 1)$ with probability density function $f(h) = \frac{h^{N_t-1}}{\Gamma(N_t)} e^{-h}$, the probability that $\beta^t \|\mathbf{h}^t\|^2 / (G\sigma^2) > \hat{g}_{th}$ can be derived as

$$\begin{aligned} q &= \Pr\left(\frac{\beta^t \|\mathbf{h}^t\|^2}{G\sigma^2} \geq \hat{g}_{th}\right) \\ &= \sum_{i=1}^T \Pr(\beta^t = \hat{\alpha}^i) \Pr(\|\mathbf{h}^t\|^2 \geq \frac{G\sigma^2}{\hat{\alpha}^i} \hat{g}_{th}) \\ &= \frac{1}{T} \sum_{i=1}^T \int_{\frac{G\sigma^2}{\hat{\alpha}^i} \hat{g}_{th}}^{\infty} f(h) dh \\ &= \frac{1}{T} \sum_{i=1}^T \sum_{j=0}^{N_t-1} \frac{1}{j!} \left(\frac{G\sigma^2}{\hat{\alpha}^i} \hat{g}_{th}\right)^j e^{-\frac{G\sigma^2}{\hat{\alpha}^i} \hat{g}_{th}}, \end{aligned}$$

which is (14).

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